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The Chemistry of Saudi Arabian Sand: A Deposition Problem on Helicopter Turbine Airfoils

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THE CHEMISTRY OF SAUDI ARABIAN SAND:
A DEPOSITION PROBLEM ON HELICOPTER TURBINE AIRFOILS

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SUMMARY

Recent operations in the Persian Gulf have exposed military helicopter turbines to excessive amounts of ingested sand. Fine particles, less than 10 μm , are able to bypass the particle separators and enter the cooling and combustion systems. The initial sand chemistry varies by location, but is made up of a calcium aluminum silicate glass, SiO_2 low quartz, $(\text{Ca},\text{Mg})\text{CO}_3$ dolomite, CaCO_3 calcite, and occasionally NaCl rocksalt. The sand reacts in the hot combustion gases and deposits onto the turbine vanes as CaSO_4 , glass, and various crystalline silicates. Deposits up to 0.25 in. thick have been collected. Although cooling hole plugging is a considerable problem, excessive corrosion is not commonly observed due to the high melting point of CaSO_4 .

INTRODUCTION AND BACKGROUND

By December 1990, turbine performance losses were reported for Black Hawk personnel transport helicopters operating in the Persian Gulf. Engine teardown and rehab tests verified that sand erosion of compressor airfoils accounted for most of the loss. At this time, unusual amorphous deposits were observed on the leading edges of the first stage turbine vanes. An example of a clean vane (aluminized X-40) is shown in figure 1. While there was no indication of hot corrosion and the deposits were easily removed in a cleaning procedure, they were also quite thick (up to 0.25 in.) and covered a portion of the airfoil (up to 0.5 in. long). An example of such a deposit is shown in figure 2. There was concern over the exact nature of these deposits and the potential for future corrosion problems. The cooling passages in these engines also contained a talc-like brown powder whose corrosive properties were also a concern. The connection between ingested sand, vane deposits, and cooling passage powders was the focus of this analytical study.

ANALYSES AND DISCUSSION

Three sand samples were obtained for analysis from the Dhahran area, two from dunes and one from a dried river bed. Deposits and cooling passage powders were obtained from four turbine engines. They were analyzed by atomic emission and absorption spectroscopy, XRD, SEM, DTA, and metallography.

Composition. - The chemical analyses shown in table I are the averages of similar sand, powder, and deposit samples. The elemental compositions (including C and S) have been converted to their corresponding oxides and normalized to 100 percent by weight. This facilitates direct comparison to complex silicate, carbonate, and sulfate compositions in the literature. However, the exact phases present can only be determined by the XRD results. The data is displayed graphically for the major and minor elements in figures 3 and 4.

The dune and river bed samples were primarily SiO_2 , with minor amounts of Al_2O_3 , CaO , NiO , Fe_2O_3 , MgO , and K_2O . Carbon and sulfur were present as carbonates and sulfates. X-ray diffraction identified low quartz as the primary phase, while some larger particles contained CaCO_3 calcite.

Course +200 μm particles (stones) separated from the river bend sand contained substantially less SiO_2 and higher amounts of CaO , MgO , carbon, and sulfur. X-ray diffraction was consistent with this result as CaCO_3 and $(\text{Ca,Mg})\text{CO}_3$ were identified as the major phases. More recent sand samples show frequent occurrences of CaCO_3 and one case of NaCl from a salt lake bed (King Fahd International Airport region).

The cooling passage powders were high in silica but not as high as the as-received sand. They were comparatively high in Al_2O_3 and Fe_2O_3 , with increases in minor elements, such as NiO , TiO_2 , and Cr_2O_3 . X-ray diffraction identified only quartz and possibly CaSO_4 . Erosion of stainless steel and Ti-6Al-4V compressor hardware accounts for additional metals in the powders. The high Al_2O_3 content of these powders can be accounted for by the high Al_2O_3 content of the fines in the sand, 14 percent Al_2O_3 for -20 μm particles (not shown in table I) versus 2.5 percent Al_2O_3 overall. Since the powders were less than 10 μm , they more closely represent the composition of the fine sand actually entering the turbine.

The resultant deposits were related to the chemical factors above. The levels of SiO_2 , Al_2O_3 , Fe_2O_3 , and minor compressor alloying elements were similar to those of the powders. However, CaO and S increased, consistent with the CaSO_4 found on the inner surface of the deposit by X-ray diffraction, while carbon decreased. $\text{CaO}\cdot\text{MgO}\cdot 2\text{SiO}_2$ diopside was the major crystalline phase, while quartz was a very weak phase.

Deposit morphology. - The deposits formed at the base of the vane leading edges. In some vanes the cooling air prevented hole-plugging (fig. 2), while others were completely covered over. There was evidence of some viscous glassy flow (fig. 5). The metallographic cross-section shown in figure 6 exhibits a featureless glassy matrix (grey), numerous large pores (black), and some second phase precipitates (lighter grey). Some bright metallic particles were also present as unreacted erosion products.

An SEM micrograph of the exterior surface (fig. 7) again reveals a smooth glassy surface with porosity. EDS analysis showed (in descending order) high intensity peaks of Si, Ca, and Al, intermediate levels for Fe (and S on the inner surface only), and low levels for Mg, Ti, Cr, K, and Na. This is very consistent with all the chemical analysis results on the deposits. The inner surface sulfur peak agrees with the CaSO_4 found on this surface by XRD.

Interpretation. - The chemistry and morphology of the deposits is explained as follows. The calcium carbonate in the sand reacts with sulfur in the fuel to form a CaSO_4 deposit. This is analogous to conventional deposition due to NaCl ingestion and Na_2SO_4 formation. CaSO_4 is a typical deposit in fluidized bed reactors where sulfur from the coal reacts with limestone and dolomite. The high Si, Al, and Ca content of the deposits and cooling passage powders is a direct result of the sand composition, especially for the fine sand, which contains more Al and more carbonates. Impaction is therefore believed to be a major deposition mechanism with respect to the silicates.

The reflective particles and Fe, Ti, Ni, and Cr in the deposits and cooling passage powders appear to be a direct result of the upstream sand erosion of compressor hardware.

The melting points of the deposits and cooling passage powders was 1137 and 1136 °C, respectively, as surmised experimentally from a broad endothermic DTA valley. This is contrasted to the high published melting points of some of the observed crystalline phases: 1713 °C for SiO₂ quartz, 1391 °C for CaO·MgO·2SiO₂ diopside, and 1540 °C for CaSO₄. A CaO·Al₂O₃·2SiO₂-SiO₂-FeO phase diagram indicates a low quaternary eutectic at 1070 °C near the deposit composition (this pseudoternary does not contain the exact deposit composition).

Molten glassy phases were thus likely only during the impaction process and would account for some viscous flow and the glassy appearance of the deposit. Since the melting point exceeds normal vane temperatures by more than 200 °C, the glass and the potentially corrosive CaSO₄ phase are not expected to be totally molten for any period of time. This is consistent with the absence of severe corrosion effects.

The porosity in the deposit can be rationalized by CaCO₃ decomposition in the deposit, if it is assumed that it first survives the hot gas path. CO₂ gas bubbles would result with an enrichment in the CaO content of the glass. This trend is consistent with the decreased C and increased Ca contents of the deposits compared to the powders (table I).

Exploratory crucible tests were performed on bulk NiAl samples to assess the corrosive behavior of the relatively pure "dune" sand, the cooling passage powder, CaCO₃, and CaSO₄ at 1000 and 1200 °C for 100 hr. The first two reagents were relatively innocuous at both temperatures. CaCO₃ formed a thick 12CaO·7Al₂O₃ scale at 1200 °C. CaSO₄ caused accelerated oxidation via NiAl₂O₄ and NiO formation, also at 1200 °C (95 mg/cm² weight change). This preliminary test suggests that some form of accelerated corrosion may be possible due to Ca compounds under severe conditions.

CLOSING REMARKS

Compositional and phase analyses have aided in the interpretation of sand-induced deposits on helicopter turbine vanes from the Persian Gulf. Fine silica-based sand containing Ca(Mg) carbonates is able to deposit as Ca-Al-Fe-silicates plus CaSO₄. Compressor erosion products are also found in cooling passage powders and the deposits. Based on the analysis of deposits to date, a serious hot corrosion problem is not expected. The situation would be more severe for aircraft operating in high NaCl regions. At this time the major concern is blocking of cooling holes and loss of aerodynamic surface. The adoption of external filter bags has been shown to reduce sand injection and is expected to also reduce deposition problems.

ACKNOWLEDGMENTS

This study would not have been possible without the concerted and timely effort of the Analytical Services Branch, especially Fran Archer (atomic emission spectroscopy) and Ralph Garlick (X-ray diffraction).

TABLE I. - CHEMICAL ANALYSIS OF RAW SAUDI SAND,
INGESTED FINE POWDERS, AND VANE DEPOSITS

[Emission spectroscopy, normalized to 100 percent oxide, averages of () samples.]

| Chemical | SAND(3) | STONE(1) | POWDER(4) | DEPOSIT(4) |
|--------------------------------|---------|----------|-----------|------------|
| SiO ₂ | 90.79 | 12.26 | 50.20 | 43.44 |
| CaO | 1.46 | 25.89 | 4.11 | 17.73 |
| Al ₂ O ₃ | 2.51 | 5.19 | 16.44 | 11.65 |
| Fe ₂ O ₃ | .84 | .85 | 15.06 | 11.43 |
| MgO | .54 | 15.64 | 2.01 | 5.77 |
| NiO | .99 | .15 | 6.12 | 4.67 |
| TiO ₂ | .19 | .20 | 1.53 | 2.18 |
| Na ₂ O | .25 | .16 | .62 | 1.41 |
| K ₂ O | .51 | .13 | 1.26 | ----- |
| Cr ₂ O ₃ | .05 | .07 | 2.19 | .98 |
| MoO ₃ | ----- | ----- | .65 | .55 |
| Nb ₂ O ₅ | ----- | ----- | .45 | .25 |
| CoO | ----- | ----- | .81 | .04 |
| Cu ₂ O | ----- | ----- | .33 | .32 |
| CO ₂ | 5.57 | 39.37 | 3.70 | .27 |
| SO ₂ | 1.27 | 8.54 | 1.01 | 4.56 |

SiO₂ quartz sand contained Al₂O₃ and CaCO₃, especially in fines. River bed stones were primarily CaCO₃ and (Ca,Mg) CO₃. Ingested powders collected from upstream compressor erosion. Vane deposits, resulting from powder impaction and reaction with sulfur, contained glassy silicates, CaO·MgO·2SiO₂ diopside, and CaSO₄. See also figures 3 and 4.

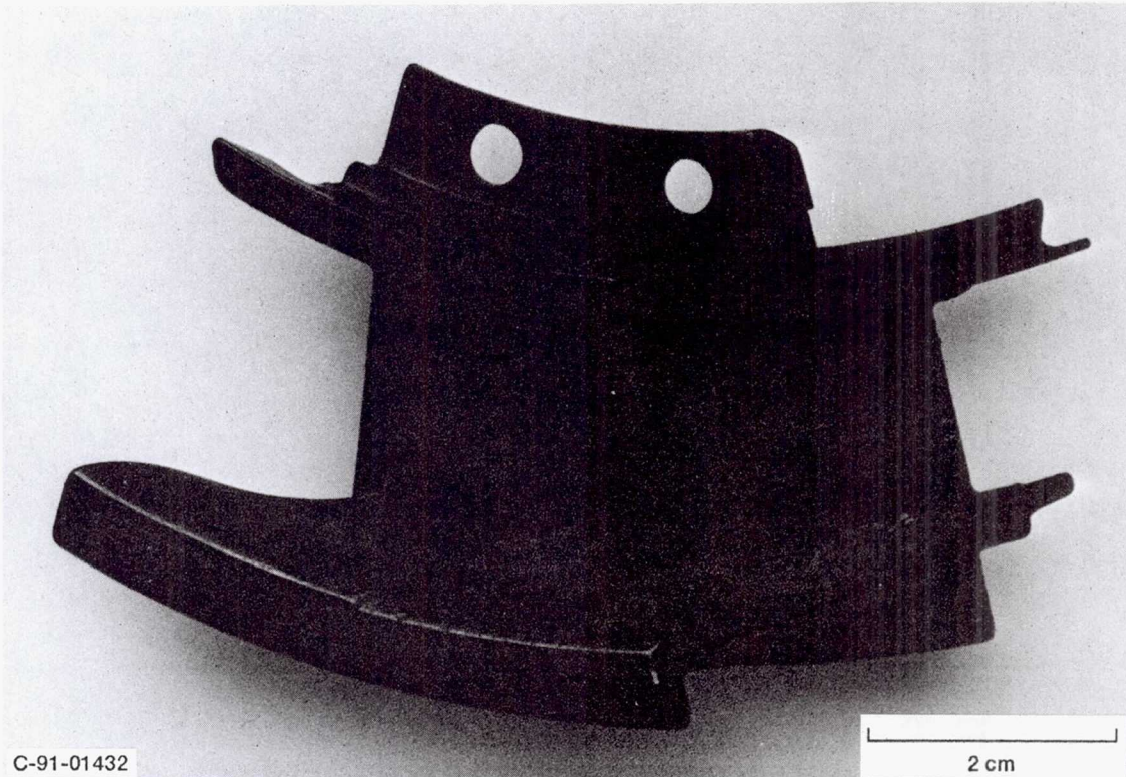


Figure 1.—First stage vane pair from T-700 turbine engine used in Black Hawk helicopters. (Codep aluminide coated X-40 cobalt alloy).

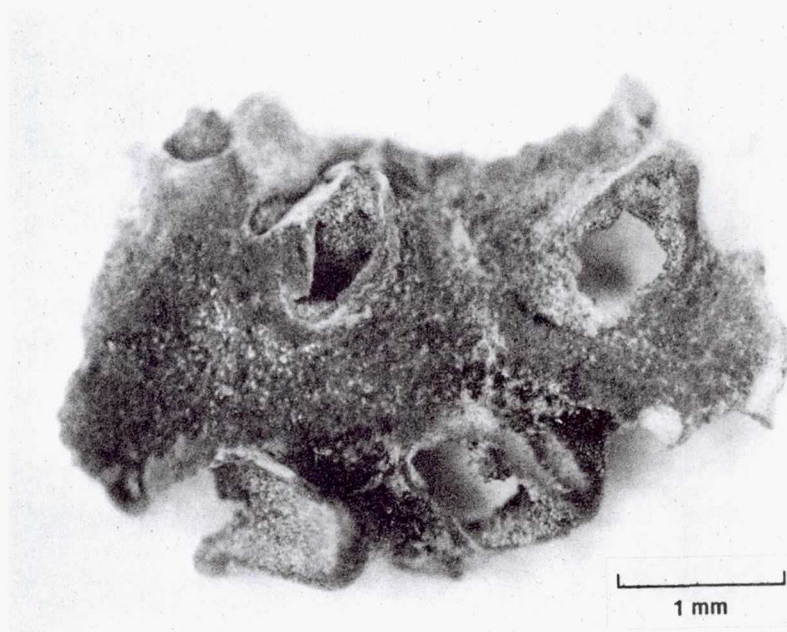


Figure 2.—Macrograph of leading edge vane deposit showing openings at cooling hole locations.

normalized weight %

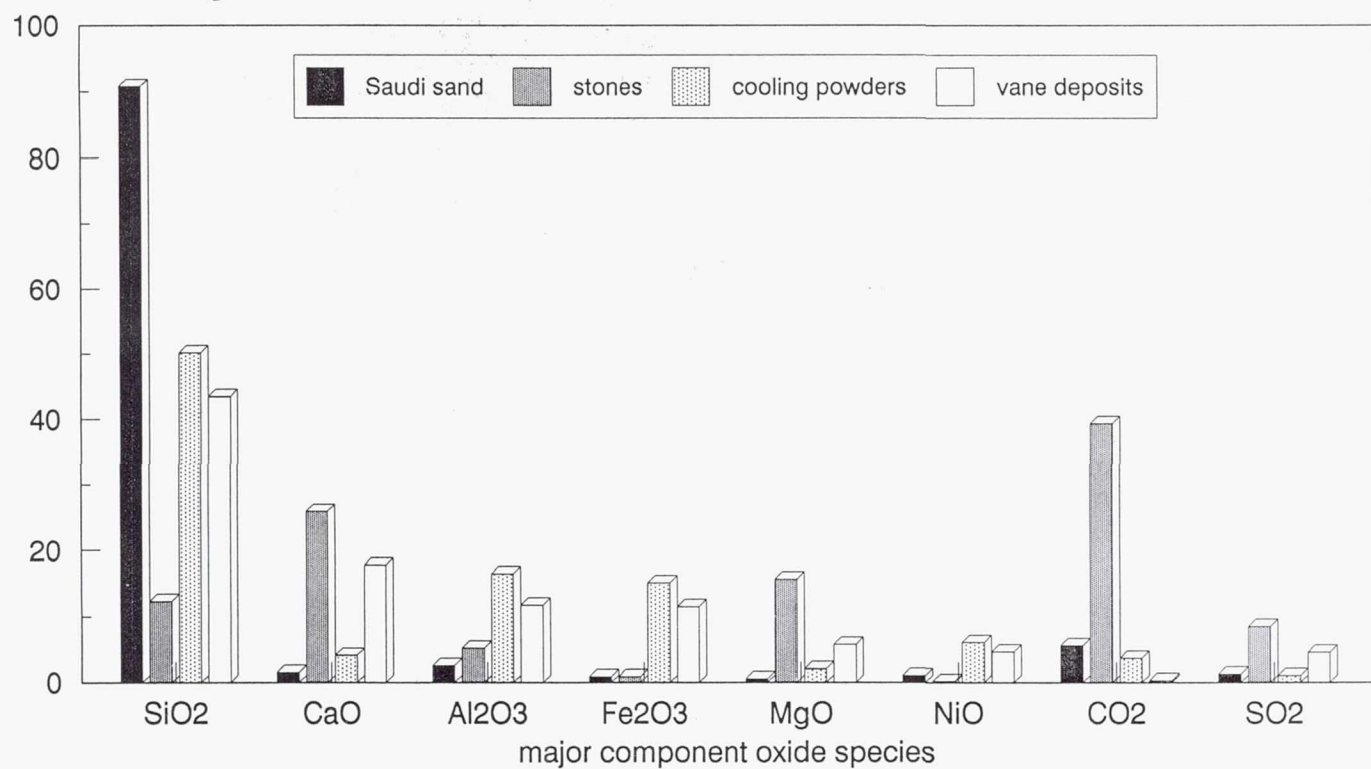


Figure 3.—Analyzed composition of Saudi Arabian sand and helicopter engine deposits. (Presented as oxide species normalized to 100% total. Averages of 3 sand and one river bed stone sample; averages of cooling passage powders and vane deposits from 4 engines). Major components.

normalized weight %

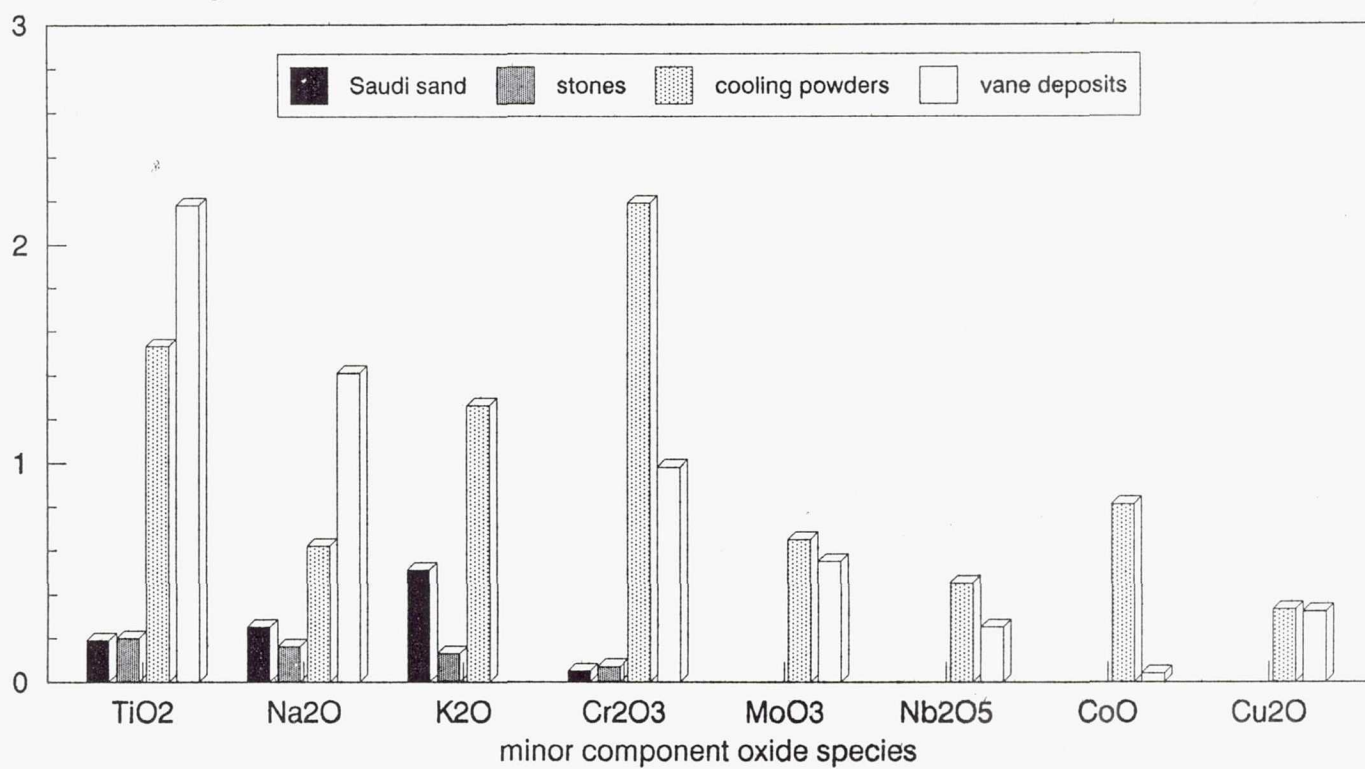


Figure 4.—Analyzed composition of Saudi Arabian sand and helicopter engine deposits. (Same considerations as figure 3).
Minor components.



Figure 5.—Macrograph of four leading edge vane deposits showing viscous flow patterns around sides.

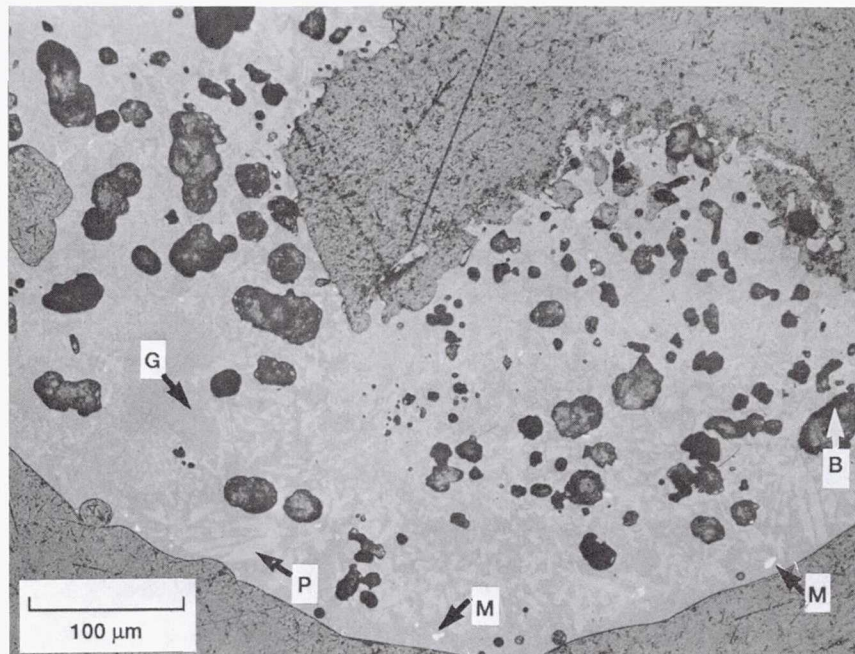


Figure 6.—Optical micrograph of vane deposit. Polished cross-section showing glassy Ca-Al-Fe silicate matrix with CaO-MgO-2SiO₂ diopside precipitates from impacted sand, Fe-Ti metallic inclusions from compressor erosion, and gas bubbles from CaCO₃ decomposition. (G = glass, P = diopside precipitates, M = metallic inclusions, B = gas bubbles).

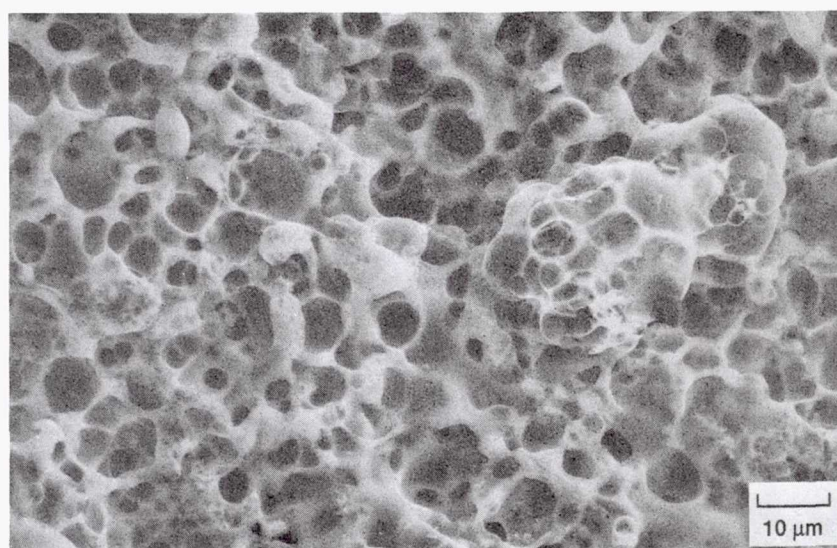
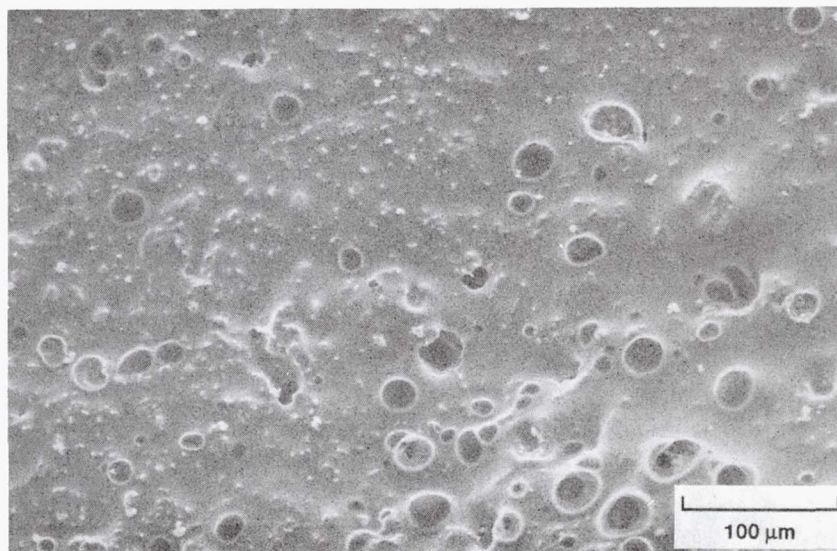


Figure 7.—SEM micrographs of glassy external deposit surface with gas bubbles.

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